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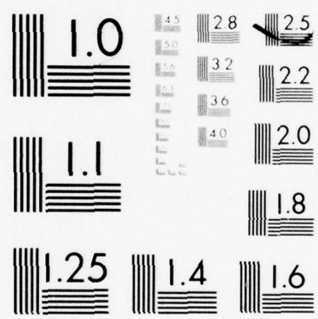

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Project Report

ETS-44

L. G. Taff

Optical Artificial Satellite Searches

2 May 1979

Prepared for the Department of the Air Force
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LINCOLN LABORATORY

OPTICAL ARTIFICIAL SATELLITE SEARCHES

L. G. TAFF

Group 94

See 1473 in back

PROJECT REPORT ETS-44

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LEXINGTON MASSACHUSETTS

ABSTRACT

This report presents a summary of the current state of optical artificial satellite searches using two telescopes. A rudimentary presentation of search strategy is given for near-stationary satellites and high inclination satellites. A complete discussion of the astrometric and photometric observing procedures necessary for identification and subsequent reacquisition is also provided. We also include a complete list of the necessary software and the minimum necessary tools that the orbital analyst requires.

CONTENTS

I. INTRODUCTION

This report consists of two interleaved parts. One part is a summary of some of the knowledge gained during the recent full searches directed by the author, at the ETS*, last Spring. The other part is a step towards the complete design of future searches based on this experience. Another report will deal with the specifics of the roughly 60[1] satellites labeled as unknown. This represents a discovery rate of $\approx$ 1 unknown/hour of search time. Since this report is an amalgam which I have attempted to weave into a continuous, logical whole, it addresses many different topics at several different levels. There is, for instance, no doubt in my mind about the Group's ability to find, track, and reacquire near-stationary satellites almost at will (given the current level of hardware and software functioning capabilities and the weather). Moreover many (5-15) such satellites can be time-shared. The search for and handling of faster (mean motion $\approx$ 2 rev/day), higher inclination (inclination $\gtrsim 20°$) satellites is in a somewhat less developed state. Hence, some sections are essentially operating manuals while others are only design considerations.

The first topic I deal with is the analysis tools necessary for the celestial mechanics of the problem. It is my opinion that the satellites of interest to GEODSS can be

*ETS = Experimental Test System

partitioned into three classes: One class is the near-stationary satellites. These satellites have low inclination ($i \lesssim 20°$), small eccentricities ($e \lesssim 0.2$), and mean motions near one revolution/day ($0.9 \lesssim n \lesssim 1.1$ rev/day). This is the second most populous class of known satellites. The most populous class of known satellites can be characterized by shorter periods (generally $n \gtrsim 2$ rev/day). Usually they also have higher inclinations (with large numbers of satellites near $i \simeq 30°$, and $i \simeq 62°$) and larger eccentricities. The third class are those with longer periods ($n \lesssim 0.5$ rev/day) with which no search experience has been acquired. Remember that extrapolating one's knowledge about the known satellite population in an attempt to delineate the unknown population is just that, an extrapolation. This breakdown of the satellite population will be continued throughout the report.

The next section is on search strategy. It is presented for a two telescope $\sim$ 150 square degrees/hour search wherein one telescope (the search telescope) actually does the searching and preliminary object discrimination and the other telescope (the support telescope) performs all of the other functions. Some of these include routine catalog maintenance, the final object discrimination on the newly discovered satellites, astrometric data acquisition, photometric data acquisition, and small area searches.

The next topic is that of the Search Dynamic Scheduler. This program does not yet exist but its potential is enormous. While successful searches can (and have) been performed without it, its availability would be a definite advantage.

After this I follow, in detail, the progress of a near-stationary satellite from its first detection to its evolution into an old, familiar friend. For the faster than near-stationary satellites such a complete presentation is impossible at this stage. Given the ability to reacquire such satellites with surety during the first hour after its discovery the presentation would be nearly identical. Following this is a summary of non-near-stationary satellite difficulties and operational modifications.

In conclusion a nearly complete list of the software needed to execute a full search is presented, given some assumptions.

Finally, this whole subject is a complex blend of celestial mechanics, orbital analysis, photometry, multi-telescope site operation, scheduling, human engineering, etc. No doubt some things have been left out or slighted. Also, I have no illusions about this document being the final word on the subject.

II. CELESTIAL MECHANICS

A. The Coordinate System

Both ETS telescopes must be in the same coordinate system. Although this is obvious, its reiteration is necessary. This means that not only the initial calibrations should be performed similarly but that the global behavior of the mount/telescope/camera combinations should be nearly identical. The latter aspect is currently impossible. As a reminder for the reader, some of the reasons for insisting on this point include the ability for rapid telescope to telescope handoff of satellites, the integrity of offsets (cf. below) taken on either telescope, the integrity of orbital element sets generated by any combination of astrometric data acquired on either or both telescopes, the ability to acquire astrometric data in the first place, and the ability to see, at will, any celestial object.

B. Astrometric Data

Positional or astrometric data refers to the reasonably accurate (< 15") measurement of the position of a celestial object. One day astrometric data may include the measurement of position and angular velocity or even distance (with two displaced, telescopes or via eclipses).

There are two completely different methods for obtaining positional data at the ETS. One uses a single nearby reference star to differentially correct for mount/telescope/camera errors. This is commonly known as Single Star Calibration (SSC). There are two versions of SSC; they only differ in the star catalogue from which the reference star to be used is chosen. One uses the SAOC (SSCSAO) and one uses the FK4 and its supplement (SSCFK4). Only SSCSAO has the requisite precision. SSCFK4 is more useful for general calibration and calibration checks. The other procedure uses several (at least 4) nearby reference stars to more thoroughly correct for mount/telescope/camera errors. This is commonly known as Precision Local Calibration (PLC).

While we can be sure that SSCSAO will meet the accuracy specifications mentioned above, PLC will invariably beat it. In fact, PLC can be good to $\approx 1''$ (see references 2 and 3). The execution time for these procedures is $10 - 30^s$ and $\approx 100^s$ respectively. The recommended mode of astrometric data acquisition consists of three (3) successive, but not rushed, SSCSAO points. The additional accuracy which can be gained from PLC is unnecessary for the purposes under discussion here. Three successive points are desired because a) it allows for a quick check on possible hardware, software, and human errors and b) it effectively constrains the freedom of an angles-only differential correction program by forcing it to match the average angular velocity.

If the telescopes were accurately globally modeled SSC would be unnecessary. Although they are not currently so modeled, uncalibrated data [commonly referred to as boresight data (which goes to a disc file) or print position data (which appears on the line printer)], if frequent enough (groups of three a second apart once per minute), and if covering a sufficiently large angular extent (30° or more), can be and has been useful.

Lastly, astrometric data should be available to all real-time orbital analysis tools. It is not at present.

C. Offsets

The offset is the vector difference between the nominal position and the real position of a celestial object. For artificial satellites this quantity has a non-zero magnitude and will change with time and position on the celestial sphere because a) the osculating orbital element set is incorrect, b) short period perturbations are absent from the differential correction process, c) small perturbations are not modeled or are incorrectly modeled, d) the mount/telescope/camera combination suffers from systematic calibration errors, and e) each operator has his own personal equation. When the offset is not dominated by telescope calibration problems it is an extremely useful tool. First of all it helps you locate the satellite. Secondly, it tells you the direction in which you should look if it's missing. In the search mode it also lightens the load on the orbital analysis tools described below precisely because it can overcome some aspects of a poor orbital element set.

D. The Ceres Problem

The three point, angles-only, initial orbit development of Gauss that was used to reacquire Ceres for Piazzi is unsuitable as an automatic orbital element set generator for the satellites of interest to GEODSS. The problem appears to be the large (5 - 70°) diurnal parallax. (In the case of Ceres, the unknown diurnal parallax was about 10" and inconsequential. The much larger heliocentric parallax of the observer was very well known). However, such a piece of software, judiciously programmed and used, can be a valuable, non-real-time aid.

For faster than near-stationary satellites an observing span of 30 - 60^m is necessary before beginning to use such a technique. For near-stationary satellites the time span needs to be 2 - 4^h. Presumably, for slower than near-stationary satellites 4 - 8^h would be necessary.

E. The Minimum Necessary Tools

There are three different types of tools necessary for the successful running and completion of a full search. As one of our major assumptions is the time-sharing of the support telescope among several (5 - 15) different satellites, one must be able to recover an unknown satellite, in the near future, from very little data. In particular, an initial observing period of 5 - 15^m duration must, together with the intelligent use of such data, be sufficient to recover the object up to $1^h.5$ later <u>without</u> having to search more than 2 or 3 field-of-views for it. Moreover, this must be done without any intermediate observations.

Where does this requirement come from? Our experience at the ETS during the recent search allows us to say that the minimum data acquisition (3 groups of 3 SSCSAO points, up to 3^m of extremely wide band photometric data for the establishment of a light curve period or its lower limit, and at least two-color photometry to establish a magnitude and color index) requires at least 9^m of telescope time. As much as 15^m may be necessary for a faster than near-stationary satellite. We also know that the "unknown"* discovery rate is roughly one per hour of search time and they occur, more or less, at random**. In addition, the subsequent observing time is at least 3^m and could be as large as 6^m. Using the geometric mean, a typical hour for the support telescope consists of (one 12^m session for a brand new "unknown") plus

*The difference between an "unknown" and an unknown is discussed in §V.

**But four unknowns per field of view has happened once and two or more unknowns per field of view has occurred several times.

(nine 5^m sessions for older unknowns). Hence, to handle 15 satellites requires the above mentioned capabilities (the numbers are rough).

For near-stationary satellites the Near-Stationary Differential Corrector (NSDC, cf. reference 4) plus the use of offsets nearly satisfies this requirement. The General Dead Reckoner (GENDR) will also nearly satisfy this requirement for these satellites. For the slower satellites the General Dead Reckoner should suffice. There is no such tool for the faster satellites. This deficiency is probably the technique which requires the most thought and work (see reference 5 where a beginning was made). The General Dead Reckoner falls short of the requirement by as much as a factor of 6 for these satellites. (There is, at present, no method for time-sharing the faster satellites.)

As observing continues during the first apparition* of the unknown, the positional data file is added to. While the requirement remains fixed, it should be easier to meet. Again, for the near-stationary satellites NSDC plus offsets will suffice. The General Dead Reckoner has not been tested in this mode (i.e., using data separated by a long time interval) for any type of satellites. For the slower satellites, the General Dead Reckoner may suffice in this mode.

*Apparition is the time interval during which a celestial object is geometrically visible.

Finally, we need to be able to reacquire unknowns at their next apparition. There are two different approaches that can be used here. The simplest is a simple differential correction program (only including J_2). One is available but untested in practice (reference 6). The other is to build a sophisticated differential corrector which will yield recovery several nights later as well as continued orbital refinement. Dr. R. Sridharan of the Laboratory's Surveillance Techniques Group (associated with the Millstone Hill Radar) has developed such a device and kindly lent it to us. It performs very well on near-stationary and faster than near-stationary satellites once enough data has been collected. This is, roughly, $2 - 4^h$ for the near-stationary satellites and $30 - 60^m$ for the faster than near-stationary satellites. I have not tested it on the slower than near-stationary satellites but would guess $3 - 6^h$ of data is necessary if their eccentricity is also small.

III. SEARCH STRATEGY

A. Near-Stationary Satellites

The search strategy currently used for near-stationary satellites is to simply sweep the topocentric equator at a rate of one hour of right ascension per hour of mean solar time. The extent in declination is determined by this constraint, the field-of-view of the telescope, the rapidity with which the telescope can be moved and stopped, the time needed to examine a field-of-view, the necessary overlap, and the time needed to handle detections. At present the declination extent is $\sim 10 - 12°$. The exact pattern of the scan within an hour block of right ascension, the exact overlap needed, the leakproof properties of the scan, etc. have never received a detailed mathematical analysis. Clearly the discovery rate of 1/hr is high enough that, what is done, is sufficient (for now) without a formal study.

Should this be performed near an equinox, the earth's shadow will eclipse a part of the topocentric equator. The satellites' diffuse reflection will be brightest just before and just after eclipse. We also do not want to detect satellites immediately prior to ingress. Hence, one simply waits until the shadow has risen high enough (altitude $\simeq 30°$) and starts the search behind (e.g., eastward) the shadow. Since it requires approximately $1^h.25$ for the shadow to sweep by*, this fits nicely with the intuitive idea that most near-stationary satellites will be detected in an hour per hour search.

It is pointless to search so late that the remaining observing time is insufficient to yield a high probability of recovery the next night or subsequent correlation. The celestial mechanical problem is in fixing the mean motion accurately. This requires at least $1 - 2^h$ of observing if the maximum next night (<u>not</u> apparition here) search is to be a $\pm$ 20^m (= $\pm$ 5°) along orbit one. Let me expand on this point in some detail: The search telescope is in the west early in the morning. Suppose the discovered satellite is near-stationary. If westward drifting, then at the start of the next evening it will be even further west, the sky will be bright, its phase angle poor, and its simply a waste of time to have looked at it initially and the next evening. If it's stationary or eastward drifting, then the search telescope will presumably find it the next night anyway.

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*The angular radius of the earth's penumbral shadow is $p = 1.02 \cdot (\pi_S + \pi_\odot + S_\odot)$ where π_S is the equatorial horizontal parallax of the satellite, $\pi_\odot$ is the equatorial horizontal parallax of the Sun, $S_\odot$ is the solar semi-siameter, and the factor of 1.02 includes the attenuation of sunlight due to the earth's atmosphere. The mean values of these quantities are 8°42'2".95 ($J_2 \neq 0$; 8°42'1".78 if $J_2 = 0$), 8".79, and 15'59".63 so p = 9°8'57". The required (mean) time is 2p/(earth's average orbital speed).

Hence, since the orbital plane can be accurately determined on 10^m of data the last satellite discriminated by the search telescope as an "unknown" (cf.§V) should be completely handled by them. This will include its change of state from "unknown" to unknown or errant known and, in either case, data acquisition. For the former case this morning's data can be used with next morning's, etc. data to refine the orbit. The next night problem for near-stationary satellites is also compounded by the demands on the telescopes. Assuming the full search to be continuing, telescope time is at a premium. Hence, extensive searching for the most recently discovered satellite not only has the lowest priority (cf.§IV), it probably won't ever be done. Assuming the time constraint limits us to a next night $\pm$ 20^m along orbit search the mean motion must be accurate to 0.02 rev/day*.

If it's a faster than near-stationary satellite the same considerations apply but the next night geometry can be considerably different. For a slower than near-stationary satellite the geometry will be constant for a few nights and, as long as proper identification is made, an orbit can be computed.

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*The average night is 9^h long at latitude 33°N. Hence, if we stop searching an hour before astronomical twilight starts prior to dawn, it will be 3:30 AM local time. We can start to look for the satellite that night at 7:30 PM local time. Hence $(2/3^d)|\Delta n| \leq 5° = 20^m$ determines Δn.

B. High Inclination Satellites

Except for a set of zero measure, every orbital element set is such that an object with those orbital elements must, sooner or later, pass through the observer's prime meridian. Moreover, all such objects will also pass, later rather than sooner, through any finite portion of the prime meridian centered on the equator. Hence, a search along the prime meridian, that covers (geocentric) declination -I° to +I°, and skips the immediate zone near 0°, can only find high inclination satellites. These will invariably be faster satellites too.

In order to get some feeling for the effects involved, consider a satellite in a circular orbit with period P and inclination i. Then, for a properly chosen, immaterial, origin of time its geocentric declination is given by

$$\sin\delta = \sin i \sin(2\pi t/P). \tag{1}$$

Let T_s be the smallest positive root of

$$\delta = I, \quad 0 \leq I \leq i. \tag{2}$$

Then the time spent between $\delta = I$ and $\delta = i$ is (due to the symmetry about $t = P/4$)

$$T = 2(P/4 - T_s). \tag{3}$$

Hence, the fraction of its period spent above I or below -I is (due to the symmetry about $\delta = 0$)

$$f = 2T/P = 1 - 4T_s/P = 1 - (2/\pi)\sin^{-1}[\sin I \csc i]. \quad (4)$$

The geometrical probability of finding it in such a search is just $100(1-f)$. This is given in Table 1 for $i = 10(10)90°$ and $I = 10(10)i$.

When we search from I_1 to I_2 and $-I_1$ to $-I_2$ ($i \geq I_2 \geq I_1 \geq 0$) the fraction of a period spent between these limits is

$$f = (2/\pi)[\sin^{-1}(\sin I_2 \csc i) - \sin^{-1}(\sin I_1 \csc i)]. \quad (5)$$

Of course, if $I_2 = i$, $I_1 = I$, this reduces to the earlier result. A full analysis must include the effects of eccentricity, the argument of perigee, and the longitude of the ascending node.

Such a scan can be made leakproof to fairly high right ascension motion ($\approx$ 100"/sec was achieved at the ETS last Spring) by either limiting its declination extent or using a larger field-of-view. The results of the search (again one interesting unknown per hour of searching time plus about one low altitude satellite per field-of-view!) lead me to believe that the analysis should be extended and this search repeated when we can handle a larger number of such satellites (cf.§IIE). When executing the search we preferentially handed over northward moving satellites. Finally, a search along the observer's prime vertical may also prove to be fruitful.

TABLE 1

Geometrical Probability of Finding A Satellite of
Inclination i Between Geocentric Declination [-I, +I]

I\ι	10°	20	30	40	50	60	70	80	90
10°	100.0	33.9	22.6	17.4	14.6	12.9	11.8	11.3	11.1
20		100.0	48.0	35.7	29.5	25.8	23.7	22.6	22.2
30			100.0	56.7	45.3	39.2	35.7	33.9	33.3
40				100.0	63.4	53.2	48.0	45.3	44.4
50					100.0	69.1	60.7	56.7	55.6
60						100.0	74.6	68.4	66.7
70							100.0	80.7	77.8
80								100.0	88.9
90									100.0

IV. THE SEARCH DYNAMIC SCHEDULER

Once the search is successfully proceeding, the demands on the orbital analyst will increase exponentially. Anything that can be routinely done with regard to optimizing scheduling should be done. Hence, a program I've called the Search Dynamic Scheduler. It doesn't exist yet and would be very different from the current Dynamic Scheduler at the ETS.

If the technical considerations behind the orbital analyst's decisions can be kept simple, then the design of such a piece of software can also be kept simple. It seems to me that given geometric visibility, no lunar complications, and a reasonable phase angle, the dominating factor influencing scheduling is the age of the satellite*. That is, the more time already invested in a particular satellite the more costly it is to lose it but the less probable the loss is. The latter follows because the longer the observing span, the less freedom there is in the orbital element set. This point of view has implicit in it the desire to successfully perform a full search. Just finding satellites is relatively easy and useless if you've already done it more than once (which the ETS staff has).

I would estimate a priority time dependence, quadratic with age, would be appropriate. I would also estimate that

*Orbital type plays an important role too, but within a single class, as outlined in §I, only age really counts.

(even if the subsequent first apparition recovery of the faster than near-stationary satellites were not a problem) the faster:near-stationary:slower satellite priorities be 4:2:1. These represent a priori weights. One must also allow for the real-time updating of these. Such factors as 1) last time observed, 2) offset time dependence, 3) satellite brightness, 4) the availability of automatic moving target indicators, 5) the number of satellites being time-shared, 6) the weather forecast, 7) the current mix of orbital types, 8) the time involved in performing the observations, 9) the current position of the telescope, etc. have to be considered. Of course, the larger one makes this list the more complex the software logic. One more factor is the discovery, during the search, of an errant known. The scheduling of this satellite for observation would also be handled by the Search Dynamic Scheduler.

Another feature is that this program would be executing continuously. No prompting by the operator would be necessary. It would interrupt the operator via bells, whistles, or by flashing messages on his CRT at the appropriate times. If we just concentrate on the a priori weights, the program could probably be rapidly implemented.

V. THE LIFE OF A NEAR-STATIONARY UNKNOWN

In this section I want to examine, in detail, the life of a near-stationary unknown. One telescope, the search telescope, is conducting an equatorial belt search as outlined above (§IIIA). The other telescope, the support telescope, is dedicated to performing routine catalog maintenance on known satellites (when it has the time; this task is of the lowest priority) and all of the other functions associated with the search except for "unknown" detection and initial discrimination. An "unknown" satellite is one detected by the search telescope (the support telescope has and will find them too) which is temporarily classed as an unknown solely on the basis of its position and angular velocity. The support telescope acquires sufficient data to classify it as an unknown or as an errant known.

A. Detection and Initial Discrimination

An artificial satellite is detected by the search telescope. Immediately a program is executed whose purpose is to attempt to identify it. This program uses only position and angular velocity for this purpose. Since identification is an extremely important function during all site operations, I describe this program's output in some detail here. (A version of this, known as Vector Element Comparison, exists at the ETS.) Once execution commences it efficiently searches for those satellites within a fixed angular distance of the telescope's current position.

Allowance is made for the size of the field-of-view (as the detected satellite is not necessarily on the telescope's optical axis) and the nearby satellites' offset history. That is, a satellite (say) nominally due east of the current position and nominally too far away has offsets which move it westward as a function of time (see Fig. 1a). Inversely, Fig. 1b shows a satellite which would *not* be considered. For those satellites passing the distance criterion the following quantities are listed on the CRT device; 1) satellite identification number, 2) its angular distance from the current position of the telescope in degrees to $\pm 0\overset{\circ}{.}1$, 3) its position angle relative to the current position of the telescope in degrees to $\pm 45°$ (or $22\overset{\circ}{.}5$ if advisable) or the appropriate symbol (e.g., 0° = N, 135° = SE etc.), 4) its angular velocity components in right ascension and declination (given an equatorial mount for the telescope) in seconds of arc per second of time to $\pm$ 1"/sec. Information concerning height above (positive) or below (negative) its orbital plane (in degrees to $\pm\ 0\overset{\circ}{.}1$) and its tardiness (negative) or earliness (positive) along its orbit (in minutes of time to $\pm\ 0\overset{m}{.}5$) is useful only when a) the satellite is on the optical axis or its offset from the optical axis is known, b) its offset history is known, and c) an experienced orbital analyst is utilizing all of this information. The detected satellite's angular velocity can be roughly gauged by actually looking at the live video picture and simultaneously being aware of the telescope's motion.

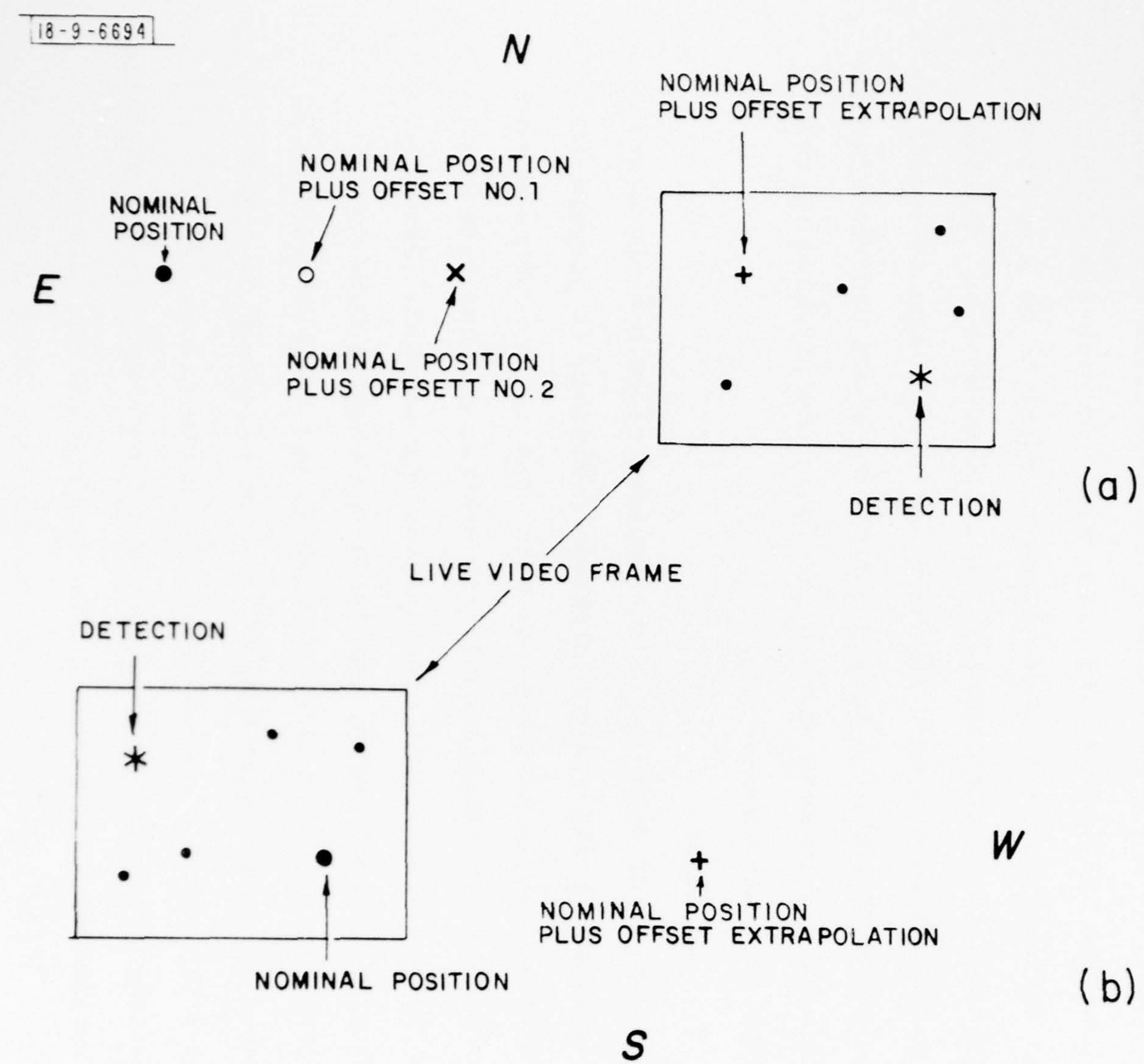

Fig. 1. a) Illustration of a westward drifting satellite that should be considered as a possible indentification for the detection. b) The inverse of the above.

Except for near-stationary satellites and the inadvertent viewing of a large eccentricity, low inclination satellite near perigee or apogee, the combination of the positional data and angular velocity data should routinely discriminate amongst the possible identifications. If, after considering all of these factors and data, there doesn't appear to be a positive identification of the detection, then it becomes an "unknown" and preparations are made for handover to the support telescope. Clearly the thread of a continuously maintained and reproducible coordinate system runs through the logic and practice of this and the next sequence of events.

B. Handover

By voice or other means the support telescope operators are notified by the search telescope operators to prepare for a handover. It is assumed that each console is routinely aware of the other's position, operating status, and can view the other's live video. This is the case for the ETS. Handover is simply accomplished by supplying the support telescope operators with azimuth and altitude to the nearest tenth of a degree. Horizon system coordinates are preferred to either equatorial system coordinates because there's less to communicate for the same accuracy and a near-stationary satellite can be tracked and recovered from an altitude and azimuth (or hour angle and declination, of course). Once in the vicinity, the search telescope's live video is used as a finding chart by the support telescope operators. As soon as the positive acquisition of the "unknown" by the support telescope occurs, its operators notify the search telescope operators who can then resume the search.

C. Initial, First Apparition*, Observing Sequence

We now have to ascertain whether the "unknown" is an unknown or an errant known. In the former case enough data must also be acquired for recovery later (cf. §IIE). In the latter enough data must be acquired to prevent its future designation as an "unknown". Since very near future ($\sim 5^m$) reacquisition by its altitude and azimuth are possible, the first thing to do is re-execute the identification program already run by the search telescope operators and then verify that all conceivable candidates for identification are in fact where they're supposed to be and different from the "unknown". For a fully operational, functioning, mature GEODSS system a known can only be labeled an "unknown" if it has maneuvered. Storing offsets on a dummy synchronous element set also provides for near term, simple, reacquisition.

If all candidates are accounted for, then the "unknown" becomes an unknown. If one or more of the candidates, assuming visibility, is not accounted for the "unknown's" status does

*Barring weather or other problems apparition ≈ night for a near-stationary satellite.

not change. In either case, as rapidly as possible, sufficient astrometric and photometric data must be acquired to support either recovery or identification. While telescope time is at a premium (remember there are other unknown's to be serviced and the discovery of the next "unknown" is not long off) recovery is more probable as the time span of the astrometric data increases. Therefore, the following sequence has been developed to optimize the conflicting demands of high recovery probability, minimum telescope time used, and high identification probability: First acquire 3 SSCSAO positional points separated by 15 - 30^s each. Then acquire a wide band set of photometric data from which a magnitude and lightcurve period (or lower limit there to) can be derived. The accuracy needed in the period is $\pm$ $0^s.01$ for periods less than 1^m. At most 3^m of photometric data is acquired at this stage. With a real-time display of the raw data, much less is usually needed. Third, we repeat the first step. Fourth, we acquire multicolor photometric data which will yield a magnitude and a color index. Fifth, we repeat the first step. An immediate analysis of the astrometric data will yield an orbital element set.

When one of the candidates was missing, we now have at least a 5 dimensional space (inclination, longitude of the ascending node, geocentric distance, lightcurve period, color index) in which to make an identification. We also used 4 dimensions already (position and angular velocity). Making a mistake now has a negligible probability. Should it prove to be an errant known all of this data is appropriately filed (including new offsets). The Search Dynamic Scheduler than takes care of scheduling additional observations so a new orbital element set can be derived. If it already evolved to an unknown, or does so at the conclusion of this step we need to follow it for the remainder of its first apparition.

D. Initial, First Apparition, Orbital Element Set

NSDC has already been executed. We now file its results, with offsets, under an appropriate identification number. This information (or the above information for an errant known) should be immediately made available to the support telescope operators. A three deep level of orbital element sets seems advisable to provide maximum protection against the inadvertent loss of a satellite.

E. Subsequent, First Apparition, Observing Sequences

Whenever the Search Dynamic Scheduler indicates another sequence of three SSC points, each separated by 15 - 30^s, is acquired. Should there be any question in the operator's mind as to the identity of the satellite, all of the resources of the Initial, First Apparition, Observing Sequence are available. New offsets are also saved.

F. Subsequent, First Apparition, Orbital Element Sets

It seems advisable to use NSDC to compute a new orbital element set immediately after each additional observing sequence and for new offsets to be acquired. The element set file for this satellite then has three element sets plus offsets. They are the most recent (brand-new element set plus new offsets), the oldest (old element set plus old offsets), and the in between (old element set plus new offsets) ones.

G. Ultimate, First Apparition, Oribital Element Set

When the Search Dynamic Scheduler indicates that the observations just made are likely to be the last of the first apparition, a new orbital element set using the more sophisticated differential correction programs should be generated, tried, and if acceptable, have offsets stored. If it's not acceptable one more observing sequence should be scheduled.

H. Finding the Satellite at the Beginning of the Second And Third Apparitions

At most we can allow for a $\pm$ 20^m along orbit search using the most recent two orbital element sets. When a satellite has been found we need to make sure its the satellite. This process is invariable and is discussed below.

I. Initial, Second and Third Apparition, Observing Sequences

One's principal purposes are to positively identify the satellite and secure enough data to allow for subsequent recovery. Hence, the entire Initial, First Apparition, Observing Sequence is repeated. The outcome of this is either a) we have the correct satellite, b) we have an errant known, or c) we have a new unknown. If it's the correct satellite, the Search Dynamic Scheduler tells us our next order of business. It it's an errant known, we proceed as above for errant known's (e.g., file the data and then proceed via the Search Dynamic Scheduler). If it's a new unknown, we proceed as above for new unknowns. Should the outcome be (b) or (c) we continue our $\pm$ 20^m along orbit search until they're completed. It's probably advisable to reinitialize the search.

Again time is of the essence. Outcome (b) is unlikely so its continued occurrence during one $\pm$ 20^m along orbit search is extremely unlikely. Outcome (c) becomes less probable as the GEODSS system matures operationally but does present a real scheduling problem during its early stages (remember we found four [4!] unknowns in a single field-of-view).

Finally, if the second effective apparition (due to weather, etc.) is not the next night, it may be advisable to immediately label the unknown lost unless the recovery probability is very high (cf. §IIIA).

J. Initial, Second and Third Apparition, Orbital Element Sets

A new orbital element set (in all cases so far discussed, it has been assumed that the reader has understood that <u>all</u>

of the acquired astrometric data is being used to generate the next orbital element set) should be immediately generated using the most sophisticated differential corrector available. Offsets are saved on it, on the set used to recover the satellite, and the penultimate set generated during the previous apparition.

K. Subsequent, Second and Third Apparition, Observing Sequences

One's aim is to "pin down" the orbital elements. The Search Dynamic Scheduler automatically handles this by scheduling the usual 3 SSC points plus the saving offsets as appropriate. We now begin to even out the frequency of data acquisition with orbital phase too.

L. Subsequent, Second and Third Apparition, Orbital Element Sets

In general, they should be unnecessary.

M. Ultimate, Second and Third Apparition, Orbital Element Sets

These are necessary, and the prescription for the Ultimate, First Apparition, Orbital Element Set should be followed.

N. Finding the Satellite at the Beginning of the N'th (>3) Apparition

This should be a routine matter, as routine as finding any known satellite. Of course, all of the resources used on preceeding nights for recovery or identification are available.

O. Initial, N'th (>3) Apparition, Observing Sequence

This, under normal circumstances, would just be our usual 3 SSC points plus the saving of offsets. In unusual circumstances our other techniques can be used.

P. Initial, N'th (>3) Apparition, Orbital Element Set

The continued real time generation of new orbital elements sets should be unnecessary. The satellite's orbit can be refined during day-time hours.

Q. Subsequent, N'th (>3) Apparition, Observing Sequences

This, under normal circumstances, would consist of the usual 3 SSC points plus the saving offsets and additional photometric data if it is desired. One might look for spin rate changes, color changes with aspect or phase angle, etc. Even more now, we attempt to fill out the orbit with the addition of more astrometric data.

R. Subsequent, N'th (>3) Apparition, Orbital Element Sets

Unnecessary (cf. above).

S. Ultimate, N'th (>3) Apparition, Orbital Element Set

Unnecessary (cf. above).

T. Satellites That Drift In and Out of Coverage

The term near-stationary includes those satellites that can drift out of sight for several days and then return. The recovery, observing sequence, orbital element set generation, etc. immediately following this hiatus should be treated as if it were the second or third apparition of the object.

VI. THE LIVES OF NON-NEAR-STATIONARY SATELLITES

This section will not be patterned after the preceding one. Rather, it is the difficulties of handling these types of satellites and their differences from the near-stationary satellites that I will concentrate on. In any case the very beginnings (Detection and Handover), and from the end of the first apparition onward (Ultimate, First Apparition, Orbital Element Set) would go substantially, if not identically, the same.

The principal problem with the faster satellites are the practical complexities of actually performing the first apparition observations. The principal problem with the slower satellites is the lack of observational experience.

A. Faster Than Near-Stationary

Even before we need to face the recovery problem 30 - 60^m after completion of the Initial, First Apparition, Observing Sequence, we need to face the recovery problem after moving to a reference star during the first SSC procedure. This is not a hard task for the near-stationary satellites for several reasons: The most important one is that they are near-stationary in a coordinate system that we are the center of. (While there exists a coordinate system which will make <u>any satellite stationary</u>, we can't get into it nor can we transform our observations into it unless we already know the orbital elements*). The other one is that SSC will automatically return the telescope to a pre-selected altitude and azimuth (it will also automatically return the telescope to a pre-selected satellite). Hence, it is difficult to lose a near-stationary satellite by going through the SSC procedure even though no orbital element set is yet available. (It will be difficult to lose the slower than near-stationary satellites too simply because they're so slow; $20^s \times 6''/sec = 3' =$ one-tenth the zoom field-of-view).

One partial solution to this problem is to redesign SSCSAO to be forward-looking; that is, instead of choosing the closest reference star, change the selection algorithm to choose the closest reference star in the direction that the satellite is traveling in. The additional input data would be the current telescope angular velocity. When it appeared safe, we manually implemented a forward-looking SSCSAO by visually checking the location of the chosen reference star on the electronically generated finding chart. If it was in the correct direction, we proceeded

*To visualize it we first must use the plane of the orbit as the fundamental plane. We now rotate about the pole of this plane so that the line of apsides becomes the abscissa. This coordinate system is now forced to rotate, about its pole, with an angular speed equal to the time rate of change of the true anomaly. Unless the orbit was circular, this rotation is non-uniform. Finally, we change the unit of distance to be the satellite's instantaneous distance. If $e \neq 0$, then the coordinate system is also pulsating at a frequency $= 2\pi$/period as it rotates.

with the SSC procedure. When it wasn't, the telescope was inhibited from automatically driving to the reference star and we availed ourselves of the NO DATA option. We then waited a few seconds and tried again.

One thing that helped here was the ability to store an arbitrary angular velocity in the computer and, at will sometime later, force the telescope to drive at those rates. Hence, if the satellite is momentarily lost, by using this feature (assuming it's still in the field-of-view!), the satellite will remain stationary while the stars move. This can enhance visual and automatic moving target indicator detection.

In any case, without an accurate global calibration of the mount/telescope/camera combination, the initial recovery problem will have to be solved. Hence, the initial acquisition of astrometric data for these satellites will likely remain a difficult task.

Before you assume that global calibration solves all of our problems with these satellites, remember it only simplifies steps 1, 3, and 5 of the Initial, First Apparition, Observing Sequence. Steps 2 and 4 (the photometry data acquisition) are still essentially impossible. The nature of the problem is that to acquire photometric data the satellite must be held, for relatively long periods of time (20 - 200^s)

within the photometer's aperture. For a variety of reasons (night sky brightness, star passage, etc.) it is desirable that this be small ($\sim$20"). In general, the manual controls on the telescope used by a skilled operator are not sufficient to meet these constraints. Without photometric data and no orbital elements (even preliminary ones), even if the satellite can be recovered 30 - 60^m later, we can't identify it.

Having convinced the reader that the Initial, First Apparition, Observing Sequence probably can't be done, I will again remind him that time-sharing these satellites is extremely difficult and dangerous. Hence, simply give up the time-sharing concept. At a discovery rate of $\sim$1 (hour of search time) if we systematically reject the southward moving satellites (since they'll set* before we can acquire enough data to recover them at the next apparition anyhow), then we'll probably have a sufficiently low enough handover frequency that the total resources of the support telescope can be directed to continuously tracking one satellite. This still means 4 - 6 unknowns/night**. We did this and it works. Of course, all astrometric data is uncalibrated (and can be 10' off) so a high density is needed. We settled on

*But see the discussion in §IIIA too.

**The search telescope abandons the fence for the last one and handles it itself. The average night is 9^h long.

a group of three points, one second apart, one group per minute. The groups of three were combined to give an average point and then the data analyzed (remember this satellite is being manually tracked and this procedure gets very boring very quickly). After an hour or so the three angles-only initial orbit procedure (with angular rates if available) would be used to start the sophisticated differential corrector. While one might think that there's no rush in computing the orbit, since we're not really time-sharing anymore, there is. For if the next apparition of this satellite is not the next night it should be abandoned at this time. The recovery probability is just not high enough. Again, there's an accurate mean motion problem, time necessary to search, and the other demands on telescope time conflict to be resolved. We did recover one satellite on its second effective opposition, five nights after its first. (Its second geometrical opposition was weathered out). We were also <u>very</u> lucky.

Now that a very bleak picture of our success and the prognosis of our success with these satellites has been painted, surely there must be a bright point. Wrong; don't forget such a satellite may be discovered during a near-stationary search and vice-versa. You also can't ignore all of the other satellites in the Search Dynamic Scheduler's queue.

B. Slower Than Near-Stationary

Extrapolating our experience with the faster than near-stationary and the near-stationary satellites, I would tend to say that current tools and techniques are adequate to handle all of the initial apparition observations. The General Dead Reckoner would play the role that NSDC did for the orbital element set generation that night. Only one orbital element set, made immediately after the last observing sequence of the first night would seem necessary. Unfortunately, to start the sophisticated differential corrector the three angles-only (or plus angular velocities) device would have to be used. For something like a Vela ($n \sim 0^{d}.25$) even the General Dead Reckoner might work until the next night. The additional problem with these satellites in particular (but implicit in this entire report), is that they're likely to be faint. Everything, everything, is much more difficult when detection alone is difficult. Even moonshine won't help here.

VII. SOFTWARE SUMMARY

In this section I want to summarize the major pieces of software necessary to effect a full search. Rather than starting from the beginning, I will assume a computer, its supplied hardware, software, and peripheral devices. I will also assume (see reference 7) such things as a telescope driver, the ability to manually drive the telescope in the dome, the ability to know the telescope's current position and angular velocity, automatic data recording, and the ability to drive the telescope on any particular orbital element set. Various stellar, satellite, etc. files are also assumed, and, their real-time accessibility is presumed. I will try to follow the search through the night as one means of logically organizing the remaining software.

I am only going to be concerned with observational software. If a tape needs to be mounted or file initialized, I'll ignore it. Also, that software already existing at the ETS will be marked so#.

As part of the initial calibration procedures, we need the capability to a) manually drive the telescope in any direction# at any rate# from the operating console, b) of moving to an arbitrary point on the visible celestial hemisphere and then tracking it by specifying either right ascension and declination#, altitude and azimuth#, or hour angle and declination, subject to horizon limit warnings# and stops#, c) have the dome slit automatically following the telescope#, d) change the current hour circle and declination circle readings#, e) use an automated single star calibration procedure#, with automatic return to a preselected satellite#, altitude and azimuth#, or hour angle and declination, which fully reduces the data in real time# (i.e., so that the correct circle readings are known), f) have the multiple visibility of such output# (e.g., CRT device, line printer, magnetic tape), g) have a much more precise way of doing this#, also automated#, and with all of the return# and display# features, and h) have a global calibration technique with accompanying reference star selection algorithm, data reduction, and real-time usage.

Such things as hardware checkouts#, weather station# data being supplied to the computer, screen size#, for each field-of-view, being measured, Routine Dynamic Scheduler# initialization, Search Dynamic Scheduler initialization, observation file initialization#, communications file initialization#, extinction measurements#, weather forecasts#, clock synchronization#, recording initialization#, lunar# and solar# position predictions, Milky Way location, and bright non-stellar object location# also need to be available.

Assuming the start up has been completed at each telescope, the search telescope now begins to search. For this we need to be able a) to enter orbital element sets and file them at will#,

b) to request tracking via any orbital element set#, including the older ones under the same number#, with or without already filed offsets#, with newly acquired offsets#, or with pre-selected offsets#, c) to acquire temporary offsets#, d) to file them at will#, e) to perform an along orbit scan of arbitrary length# with arbitrary offsets both along the orbit# and perpendicular to the orbit#, f) to interrupt such scans and return#, g) to recover the last field-of-view# (for all scans#), h) to hold a particular field-of-view for all scans#, i) to perform a raster scan in equatorial coordinates of arbitrary extent and width#, j) to perform a raster scan in horizon coordinates of arbitrary extent and width, k) to perform an elliptical spiral scan, l) to use the automatic moving target indicator in the stare#, integration#, or streak# modes, m) to save# and restore# at will an arbitrary angular velocity, n) to query the computer as to the progress of any scan#, and o) to be able to graphically see the progress of a scan#.

Soon after the search commences a satellite is found. Hence we need a) the correlation programs# discussed in §VA, b) a graphical display of the vicinity#, and c) appropriate displays, in horizon and equatorial coordinates, of the telescope's commanded position#, current position#, the dome's position#, and assorted times#.

After handoff the support telescope's additional requirements for action are a) a photometer and filter wheel controlled from the operating console[#], b) the ability to acquire arbitrary amounts of photometric data via arbitrary filters[#], c) the capability to bin and display it graphically at will[#], d) to produce a paper copy of the same[#], e) to analyze it for a period, f) to calibrate the data by the use of secondary or primary photometric standards[#], g) to record and file the data[#], h) to access historical values of the data, i) a general dead reckoner[#], j) the capability of acquiring and filing uncalibrated positional data[#], k) a Near-Stationary Differential Corrector[#], l) its analog for the faster satellites, m) initial orbit generators that use angles[#] and angular rates[#], n) a sophisticated differential corrector[#], o) perhaps, if it executes very fast, a simple differential corrector[#], p) differential correctors that can use and accept angular velocity data[#], q) the ability to acquire instantaneous angular velocities, r) the ability to predict future location and velocity for an orbital element set[#] into an arbitrary long future[#] or past[#], at an arbitrary frequency[#] s) the ability to tag all data under a new identification number[#], t) the ability to merge files on the two computers[#], u) the ability to communicate astrometric data[#] and photometric data[#], v) the ability to handle different security levels[#],

w) the ability to delete from all files#, x) the ability to plan that nights work during the daytime hours#, y) the ability to have closed-loop automatic tracking, and z) the ability to intelligently use all of this.

A last word: Just because an item has a # by it doesn't mean its perfect. It doesn't even mean it works correctly. It means, at the minimum, somebody has developed and coded the first cut at a finished product. We have no finished products. We do have lots of things that work well. Remember, it's the Experimental Test System.

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This report presents a summary of the current state of optical artificial satellite searches using two telescopes. A rudimentary presentation of search strategy is given for near-stationary satellites and high inclination satellites. A complete discussion of the astrometric and photometric observing procedures necessary for identification and subsequent reacquisition is also provided. We also include a complete list of the necessary software and the minimum necessary tools that the orbital analyst requires.

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